Testing leptogenesis in low-scale seesaw mechanisms

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GDR Terascale, November 24th 2015

Based on:

A. Abada, G. Arcadi, V. Domcke and M.L., *arXiv:1507.06215 [hep-ph]*

SISSA

Leptogenesis in a nutshell

The Universe is matter dominated,
the Standard Model cannot account for the observed BAU

$$Y_{\Delta B} = (8.6 \pm 0.01) \times 10^{-11}$$

This result calls for physics beyond the SM

Sphalerons: non-perturbative solutions of the SM

$\Delta(B - L) = 0$ $\quad\quad$ ~~$B + L$~~

While sphalerons in thermal equilibrium

$$130 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$$

they convert any lepton asymmetry into a net baryon asymmetry

⬇

Baryogenesis via leptogenesis

Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N_I}\partial\!\!\!/ N_I - \left(Y_{\alpha I}\overline{\ell_\alpha}\widetilde{\phi}N_I + \frac{M_{IJ}}{2}\overline{N_I^c}N_J + h.c. \right)$$

After electroweak phase transition < Φ > = v ≃ 174 GeV

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

The Lagrangian provides the ingredients for leptogenesis too

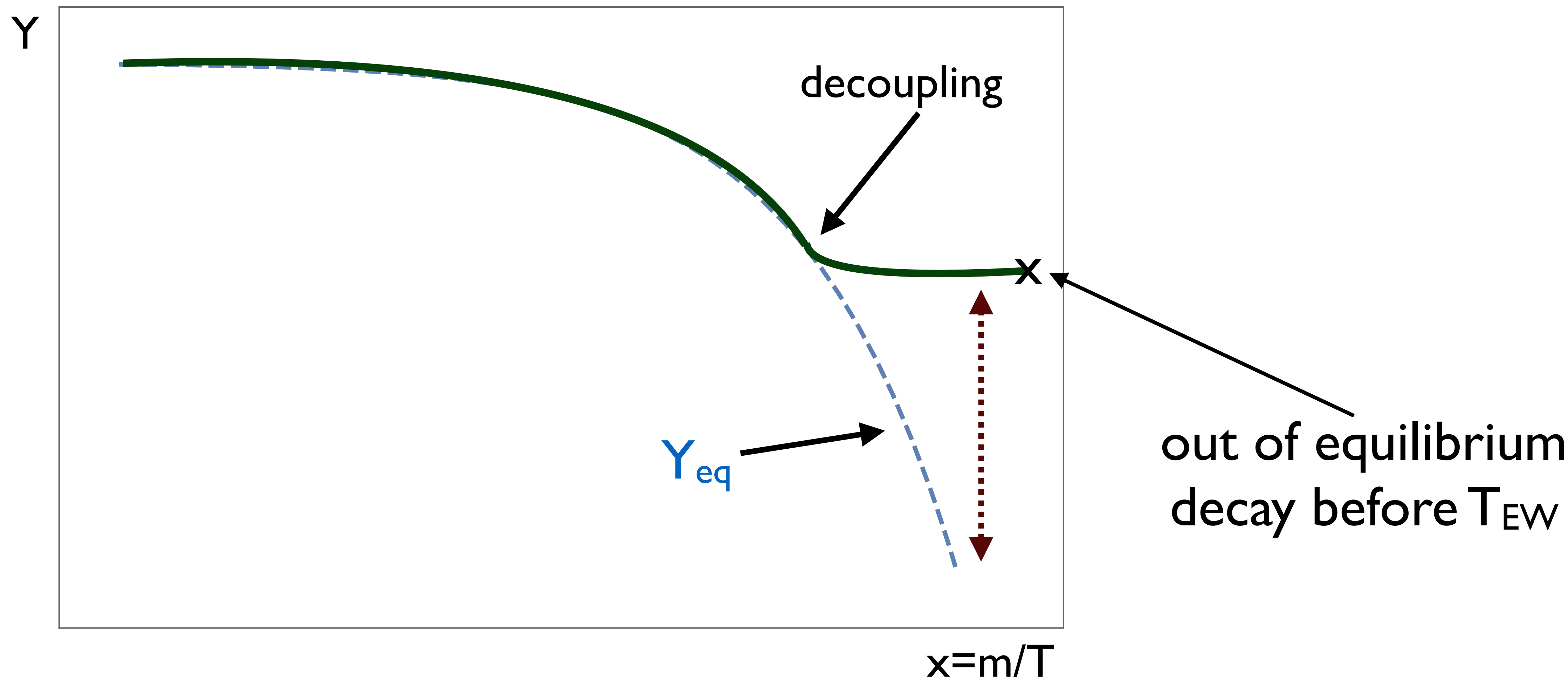
Sakharov conditions

- **Complex Yukawa** couplings *Y* as a source of $\not{CP}$ ✓
- $\not{B}$ from sphaleron transitions until $T_{EW} \simeq$ 140 GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

Thermal leptogenesis

Sterile neutrinos in thermal equilibrium if $|Y| \gtrsim 10^{-7}$

Thermal leptogenesis: sterile neutrinos in equilibrium at large temperatures



Generation of a lepton asymmetry due to the Majorana character of the particles

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45

$M > 10^8$ GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses) → Prohibitive to test in laboratory

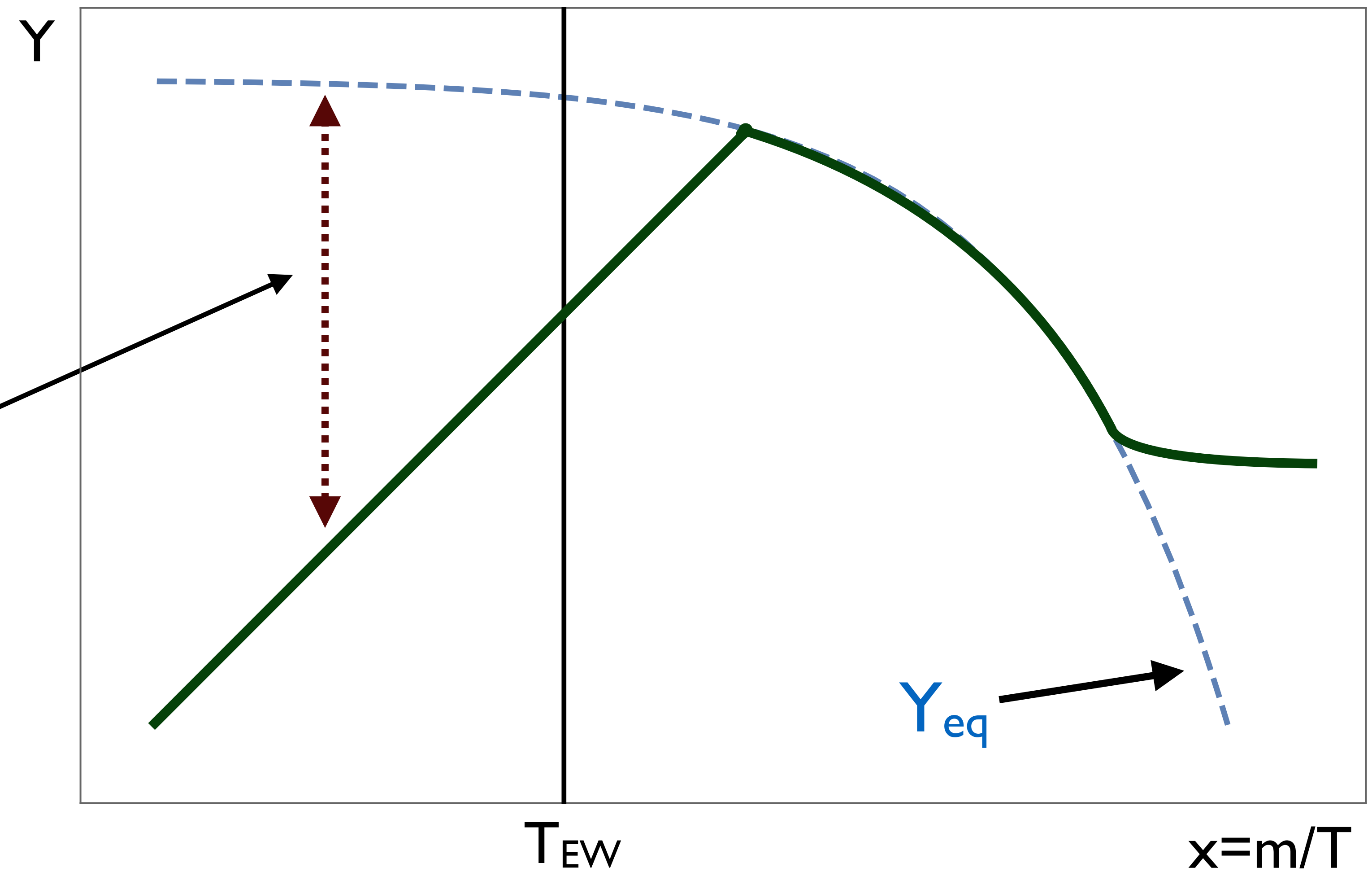
S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph]
A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281
A. Pilaftsis and T. E. J. Underwood, hep-ph/0309342

ARS mechanism

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255

Sterile neutrinos out of equilibrium at large temperatures

deviation from equilibrium before T_{EW}



From the seesaw relation

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger \simeq 0.3 \left(\frac{\text{GeV}}{M}\right) \left(\frac{Y^2}{10^{-14}}\right) \text{ eV}$$

M ~ GeV to reproduce ν masses → **Testable**

Flavoured leptogenesis

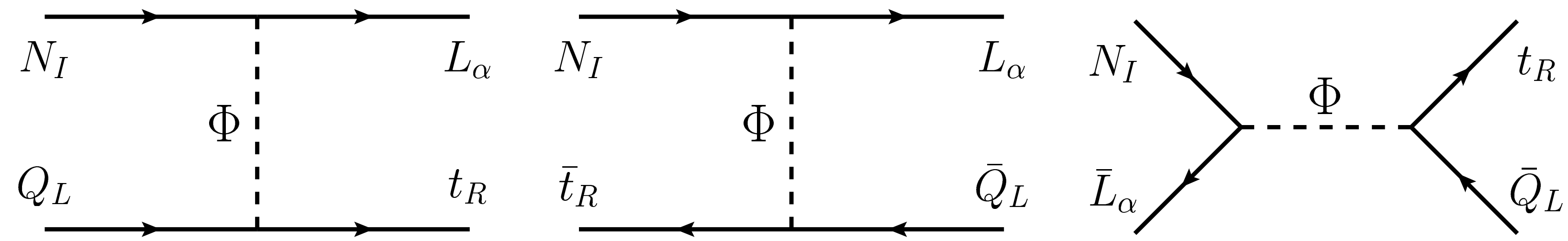
M ~ GeV ≪ T

Negligible Majorana character → total lepton number is conserved

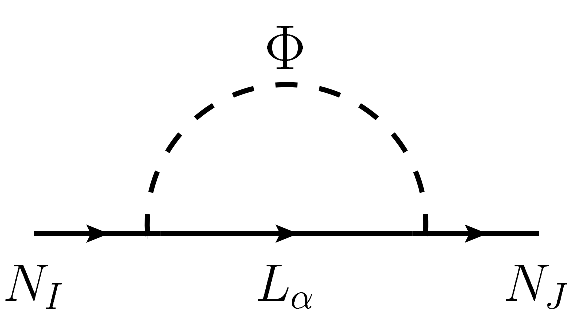
How do the mechanism work?

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255
T. Asaka and M. Shaposhnikov, hep-ph/0505013
M. Shaposhnikov, arXiv:0804.4542 [hep-ph]
T. Asaka and H. Ishida, arXiv:1004.5491 [hep-ph]
T. Asaka, S. Eijima and H. Ishida, arXiv:1112.5565 [hep-ph]
L. Canetti, M. Drewes and M. Shaposhnikov, arXiv:1204.4186 [hep-ph]
L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]
P. Hernández, M. Kekic, J. López-Pavón, J. Racker and N. Rius, arXiv:1508.03676 [hep-ph]

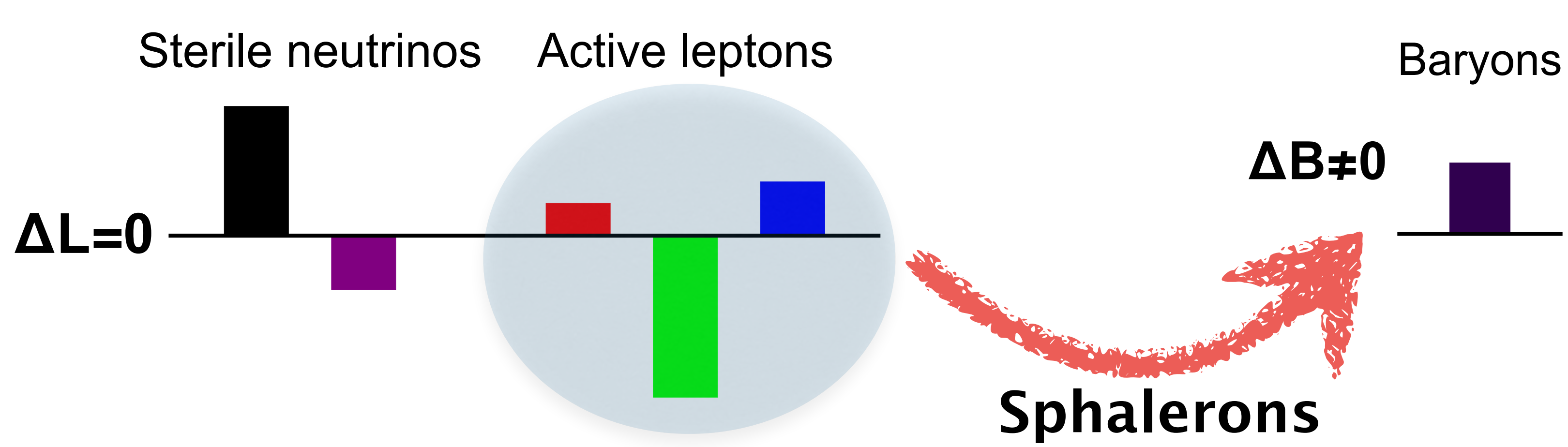
generation of sterile neutrinos



oscillation of sterile neutrinos



asymmetries in **individual** flavours arise



Naturalness argument

Need a pair of **degenerate neutrinos** or **hierarchical yukawas**:
fine-tuning or **symmetry**

Approximate lepton number at the origin of mass degeneracy

$$M = \underbrace{M_0}_{\Delta L = 0} + \underbrace{\Delta M}_{\Delta L \neq 0}$$

$$||\Delta M|| \ll ||M_0||$$ → **degenerate pseudo-Dirac pairs of sterile neutrinos**

Minimal setup: SM + 2 sterile fermions with opposite lepton number

Field content: $\underbrace{\nu_L + N_1}_{L=1} + \underbrace{N_2}_{L=-1}$

$$M_0 = \begin{pmatrix} 0 & vy & 0 \\ vy & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}$$

$m_\nu = 0$
$M_1 = M_2 = \Lambda$

"Lepton number conserving" mass spectrum

(some) Minimal mechanisms

$$M_0 = \begin{pmatrix} 0 & vy & 0 \\ vy & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}$$

Basis: (ν_L, N_1^c, N_2^c)

L=1

L=-1

Need to perturb M_0 to generate $m_\nu \neq 0$ and $\Delta M_{heavy} \neq 0$

Add small ΔL=2 operators (assume ε, ζ, ζ' ≪ 1)

$$\Delta M_{linear} = \begin{pmatrix} 0 & 0 & \epsilon vy \\ 0 & 0 & 0 \\ \epsilon vy & 0 & 0 \end{pmatrix} \qquad \Delta M_{ISS} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \zeta\Lambda \end{pmatrix} \qquad \Delta M_{loop} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \zeta'\Lambda & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Toy model (one active neutrino)

	ISS	Linear	Loop
m_ν	$\zeta y^2 \frac{v^2}{\Lambda}$	$2\epsilon y^2 \frac{v^2}{\Lambda}$	$\zeta' y^2 \frac{v^2}{\Lambda} f\left(\frac{\Lambda^2}{M_W^2}\right)$
ΔM_{32}^2	$2\zeta\Lambda^2$	$4\epsilon v^2 y^2$	$2\zeta'\Lambda^2$

$M_1 = m_\nu$

$M_{2,3} \simeq \Lambda$

Viable mechanisms (minimal setup)

Toy model

	ISS	Linear	Loop
m_ν	$\zeta y^2 \frac{v^2}{\Lambda}$	$2\epsilon y^2 \frac{v^2}{\Lambda}$	$\zeta' y^2 \frac{v^2}{\Lambda} f\left(\frac{\Lambda^2}{M_W^2}\right)$
ΔM_{32}^2	$2\zeta\Lambda^2$	$4\epsilon v^2 y^2$	$2\zeta'\Lambda^2$

$M_1 = m_\nu$
$M_{2,3} \simeq \Lambda$

Requirements

Neutrino data ← → **Successful leptogenesis**

Need a pair of

$$y < \sqrt{2} \times 10^{-7}$$ **out of equilibrium**

$$m_\nu \gtrsim \sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}\ {\rm eV}$$

$$100\ {\rm MeV} \leq M_{2,3} \lesssim 20\ {\rm GeV}$$ **relativistic**

BBN bound

$$\Delta M_{32} \lesssim 100\ {\rm keV}$$ **degenerate**

sterile neutrinos

Only ISS: too large mass splitting or too small neutrino masses
Only linear: no mass splitting when Higgs VEV v=0

The minimal framework

Linear + inverse seesaw perturbations

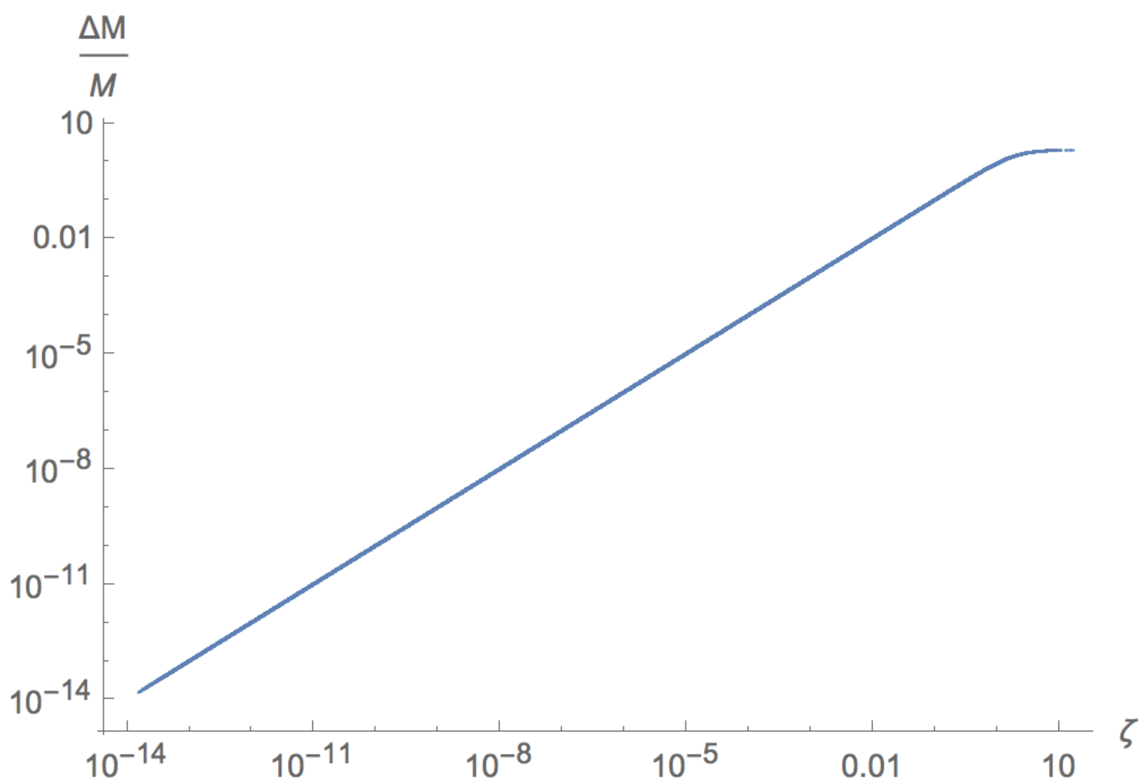
SM + 2 RH neutrinos with opposite lepton number

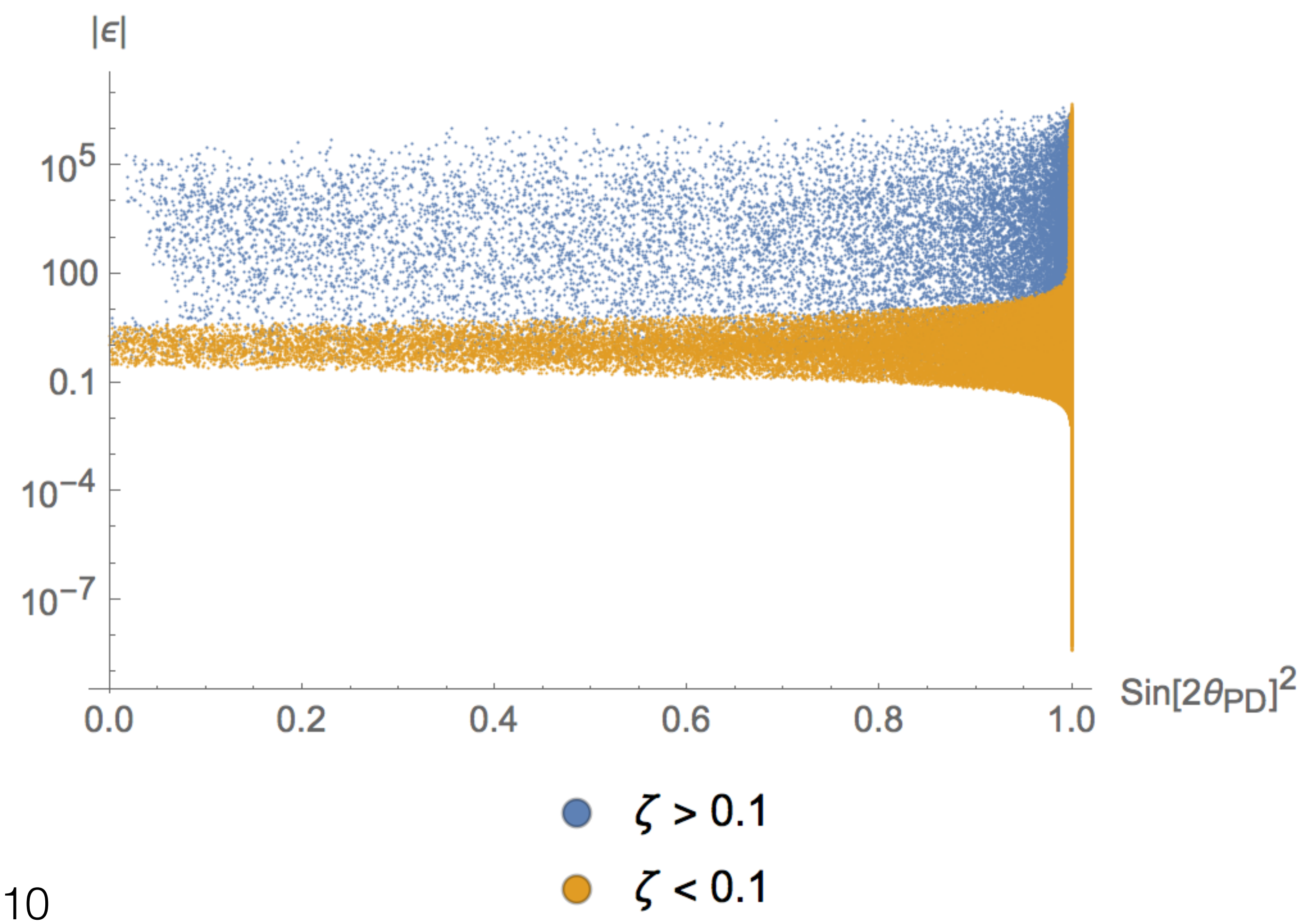
"Minimal flavour seesaw"

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez, arXiv:0906.1461 [hep-ph]

$$\mathcal{M} = \begin{pmatrix} 0 & vY & \epsilon v Y' \\ vY^T & 0 & \Lambda \\ \epsilon v Y'^T & \Lambda & \zeta\Lambda \end{pmatrix}$$

Sterile neutrino oscillations
$$\begin{cases} \zeta \ll 1 \Rightarrow \text{small mass splitting} \\ \varepsilon \ll 1 \Rightarrow \text{large mixing angle} \end{cases}$$





Weak washout regime: analytical solution

$F \equiv Y^{\text{eff}}$ $\quad |F_{\alpha I}| < \sqrt{2} \times 10^{-7}$

$$Y_{\Delta B} = \frac{n_{\Delta B}}{s} = \frac{945\, 2^{2/3}}{2528\;3^{1/3}\,\pi^{5/2}\,\Gamma(5/6)}\,\frac{1}{g_s\,(T_{\rm W})}\,\sin^3\phi\,\frac{M_0}{T_{\rm W}}\,\frac{M_0^{4/3}}{(\Delta m^2)^{2/3}}\,Tr\left[F^\dagger \delta F\right]$$

$$\mathcal{L} \ni F_{\alpha I}\,\overline{\ell_L^\alpha}\,\widetilde{H}\,N_I + h.c.$$

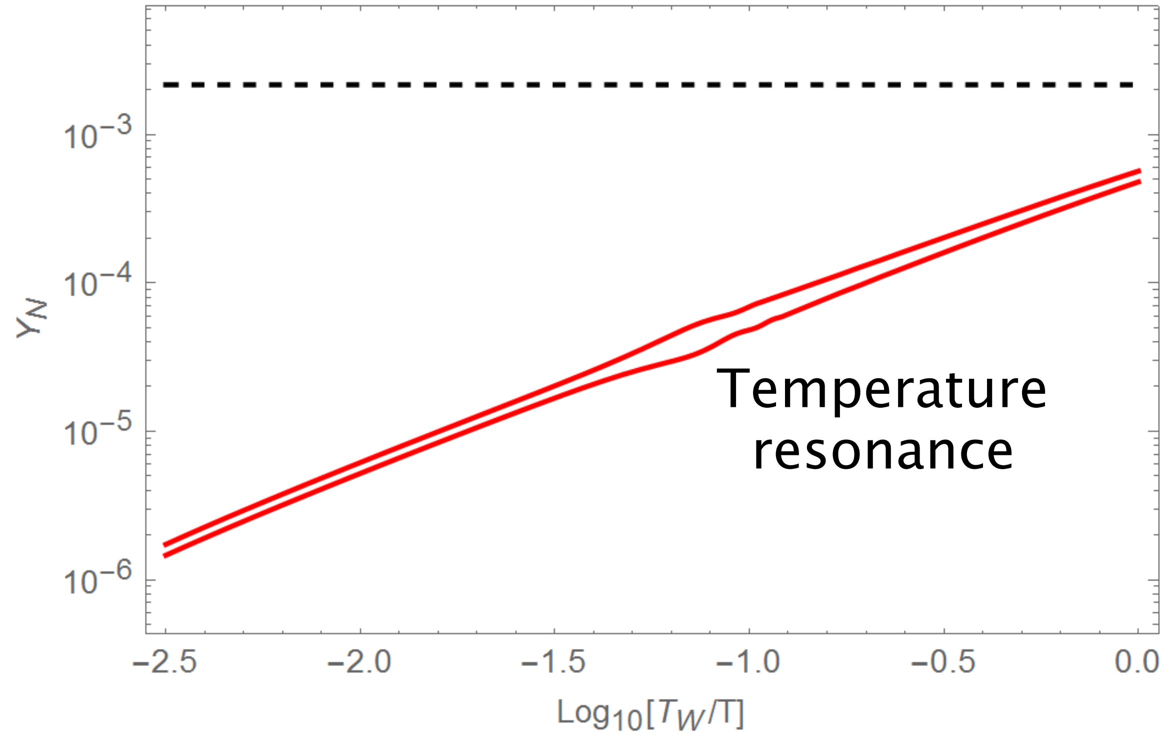
$$\delta_\alpha = \sum_{I>J} \mathrm{Im}\left[F_{\alpha I}\left(F^\dagger F\right)_{IJ} F^\dagger_{J\alpha}\right]$$

$$H = \frac{T^2}{M_0}$$

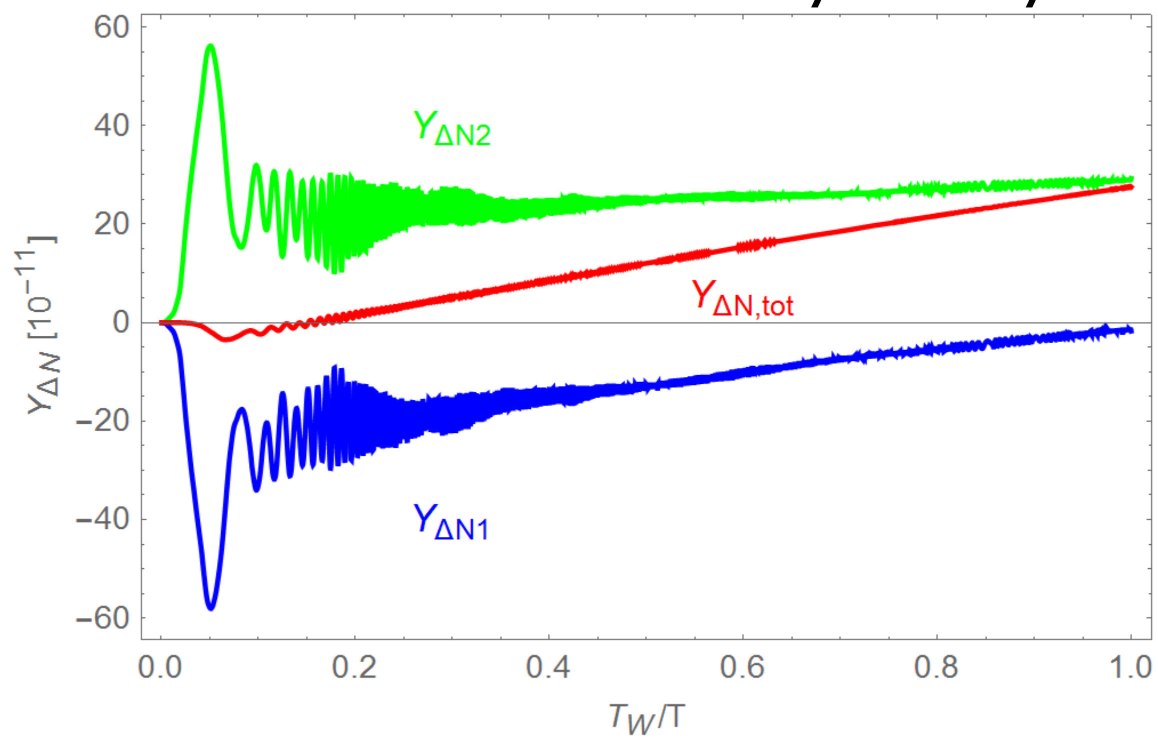
$$\frac{N_C h_t^2}{64\pi^3} = \frac{\sin\phi}{8}$$

Weak washout regime: numerical comparison

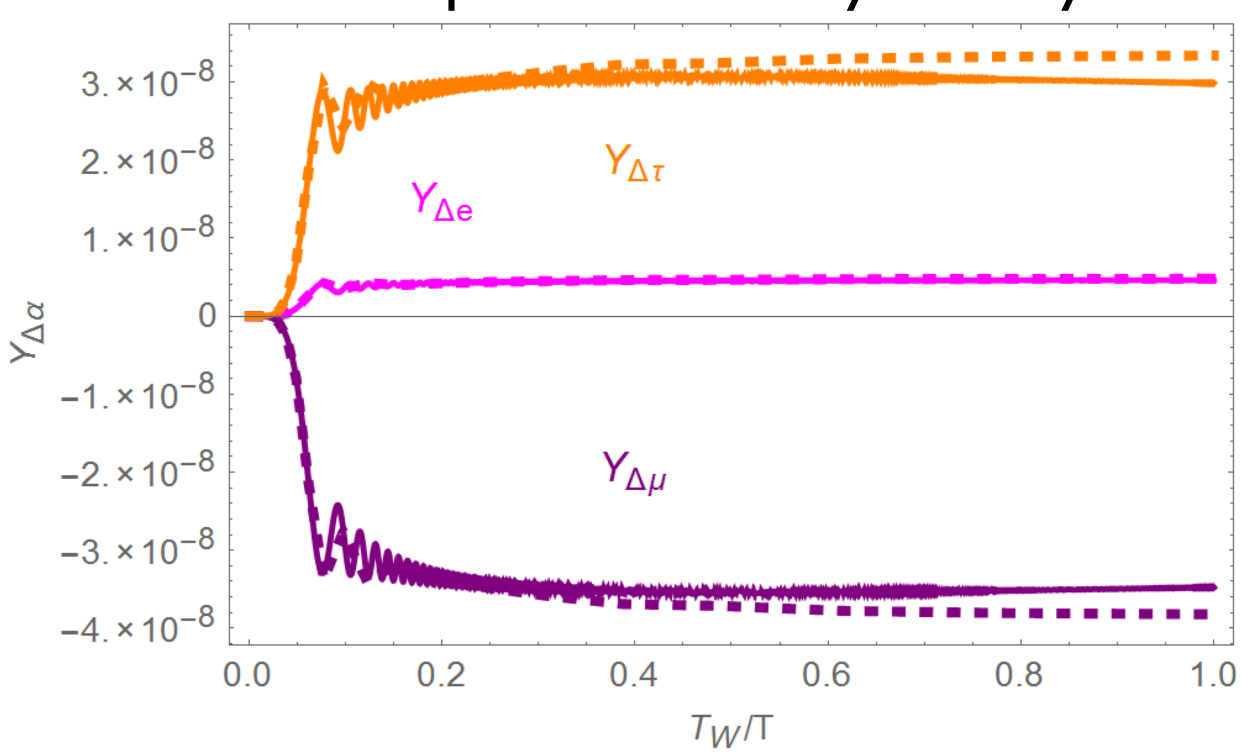
Sterile neutrino abundances



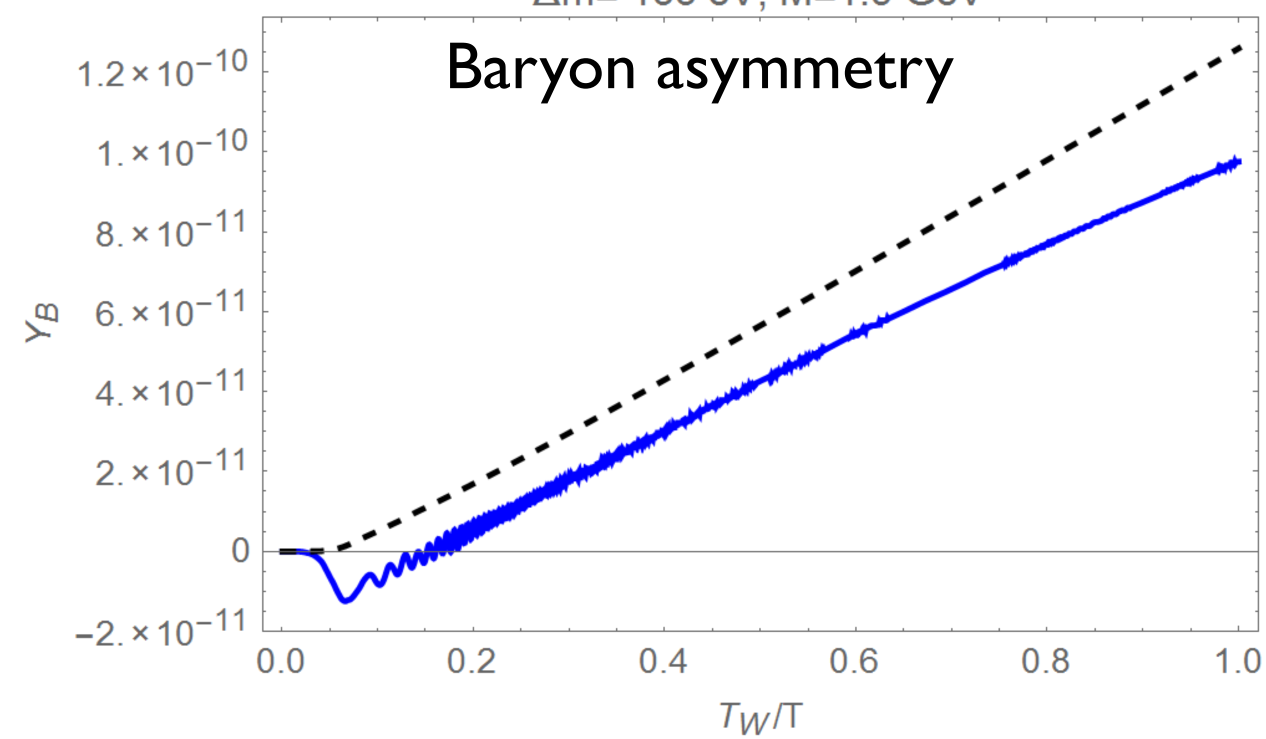
Sterile neutrino asymmetry



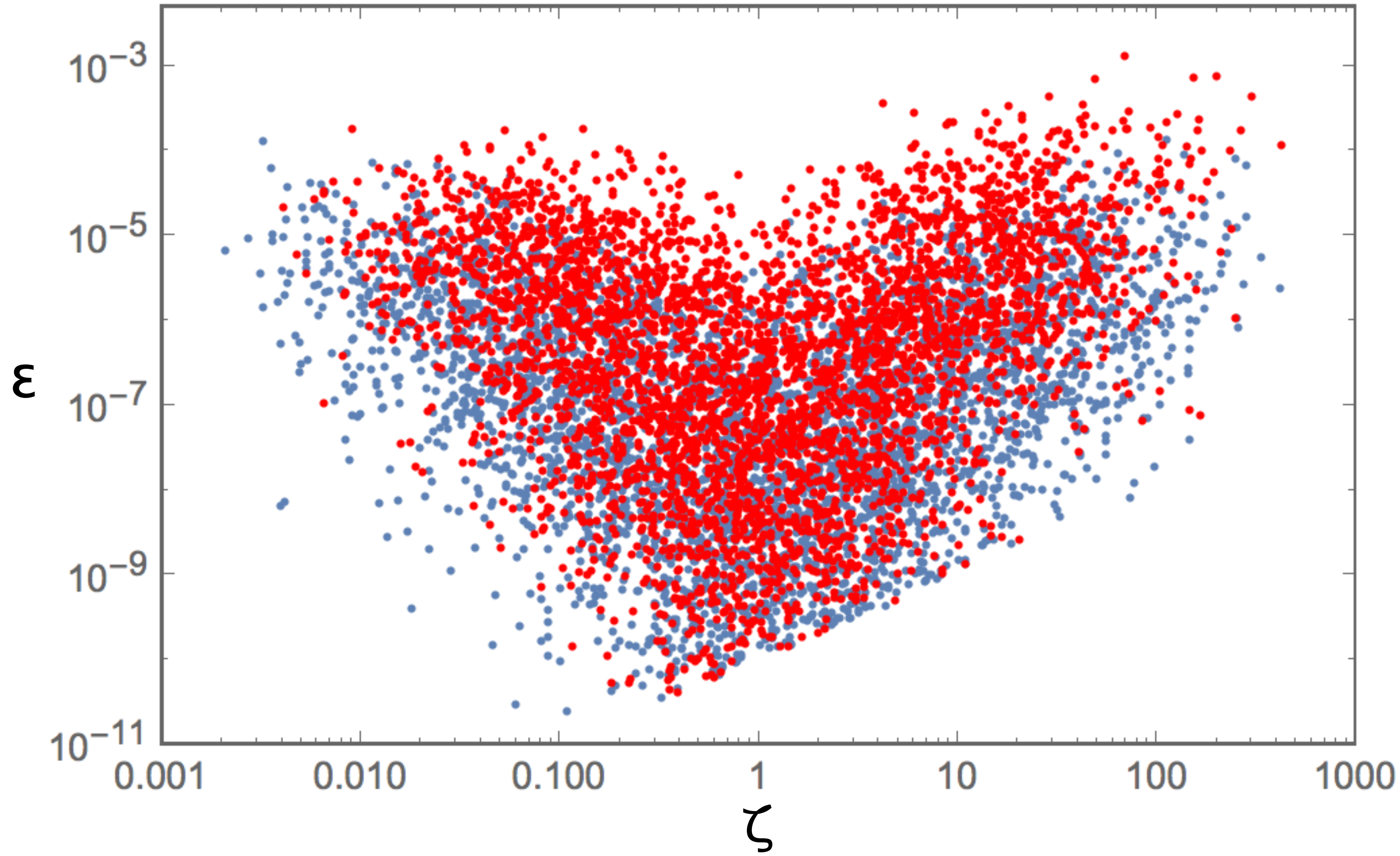
Lepton flavour asymmetry



Δm= 133 eV, M=1.5 GeV

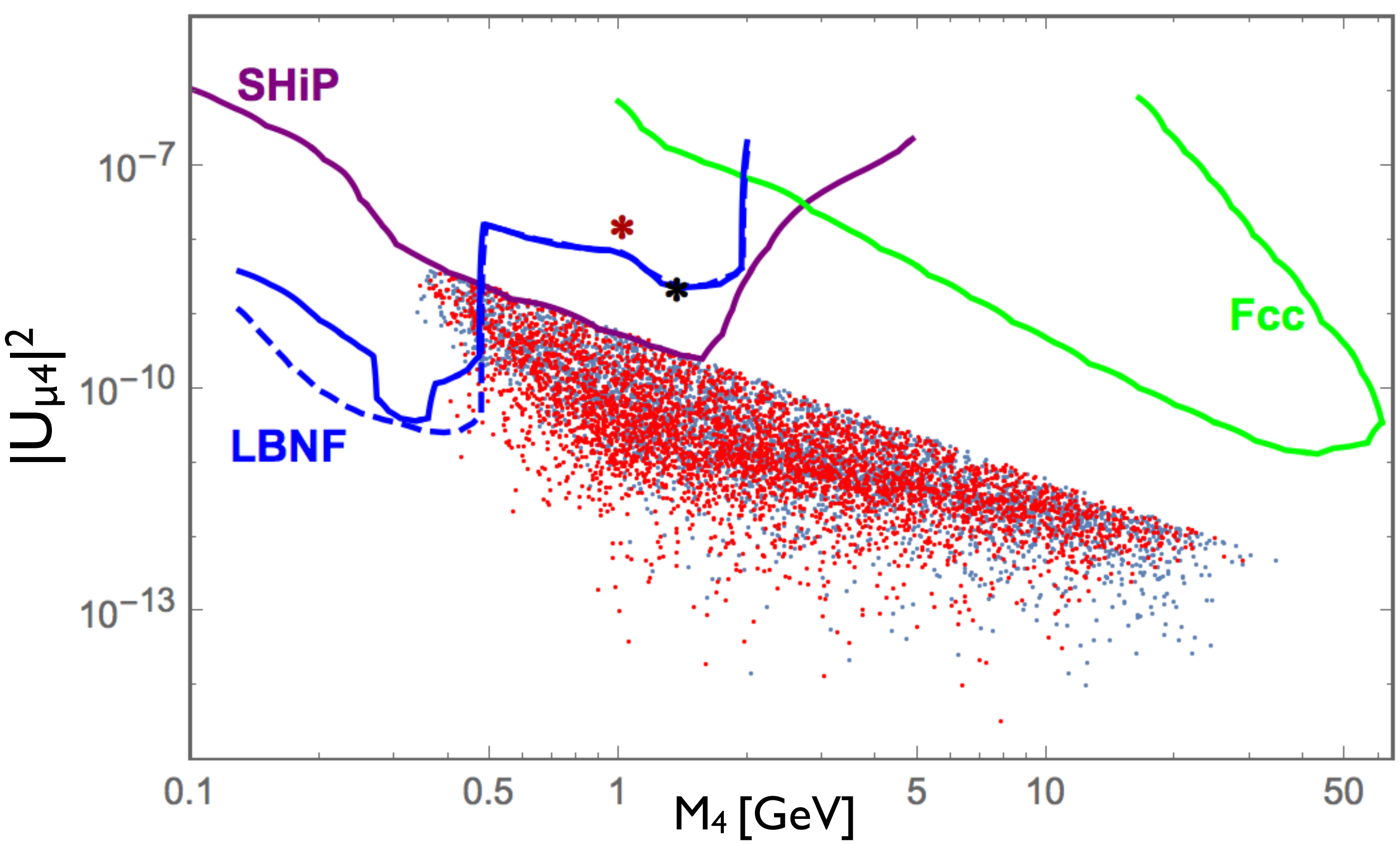


Weak washout: viable solutions



LNV parameters

Normal Hierarchy
Inverted Hierarchy



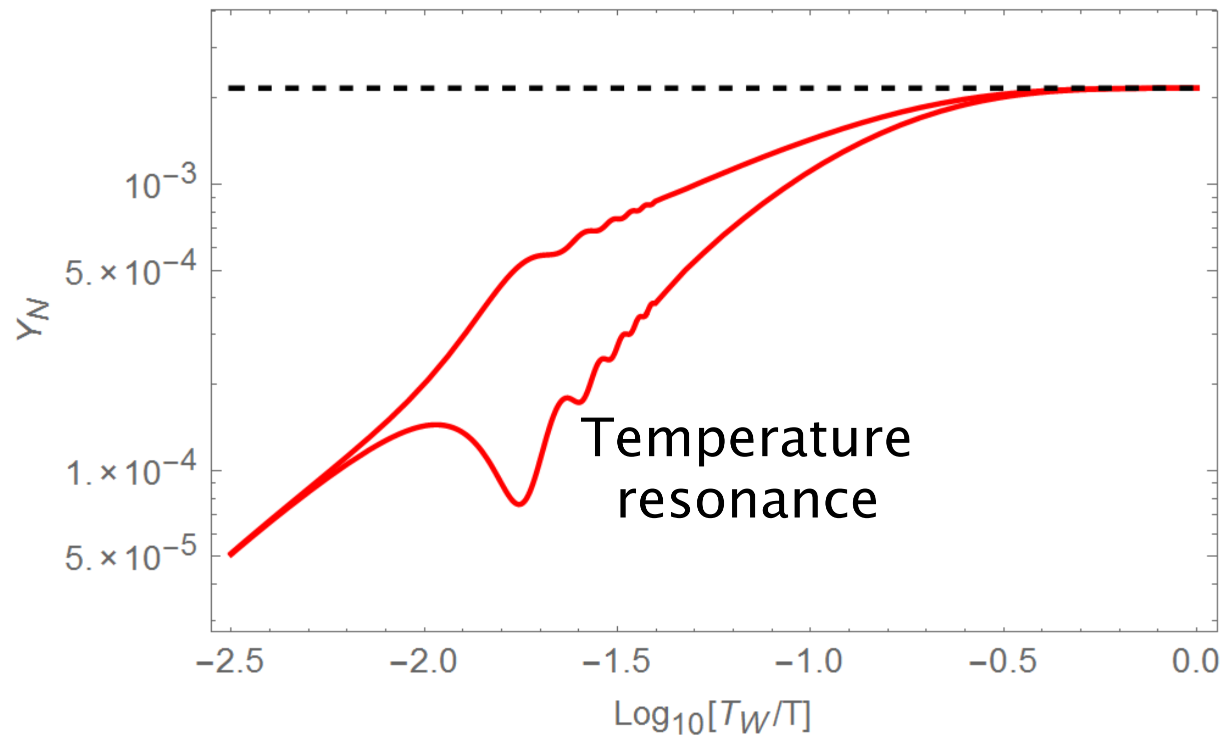
Sterile fermions phenomenology

C. Adams et al., arXiv:1307.7335 [hep-ex]
S. Alekhin et al., arXiv:1504.04855 [hep-ph]

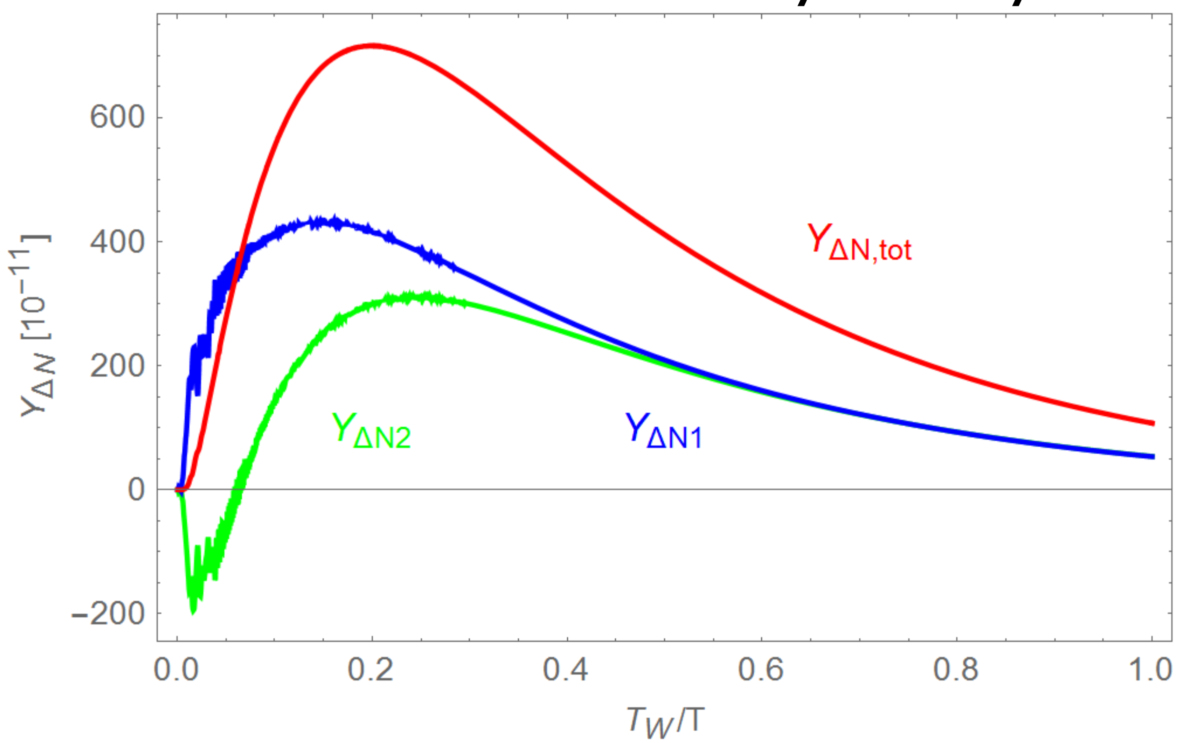
Strong washout regime: numerical solution

The analysis is computationally demanding: only a set of benchmark points is solved

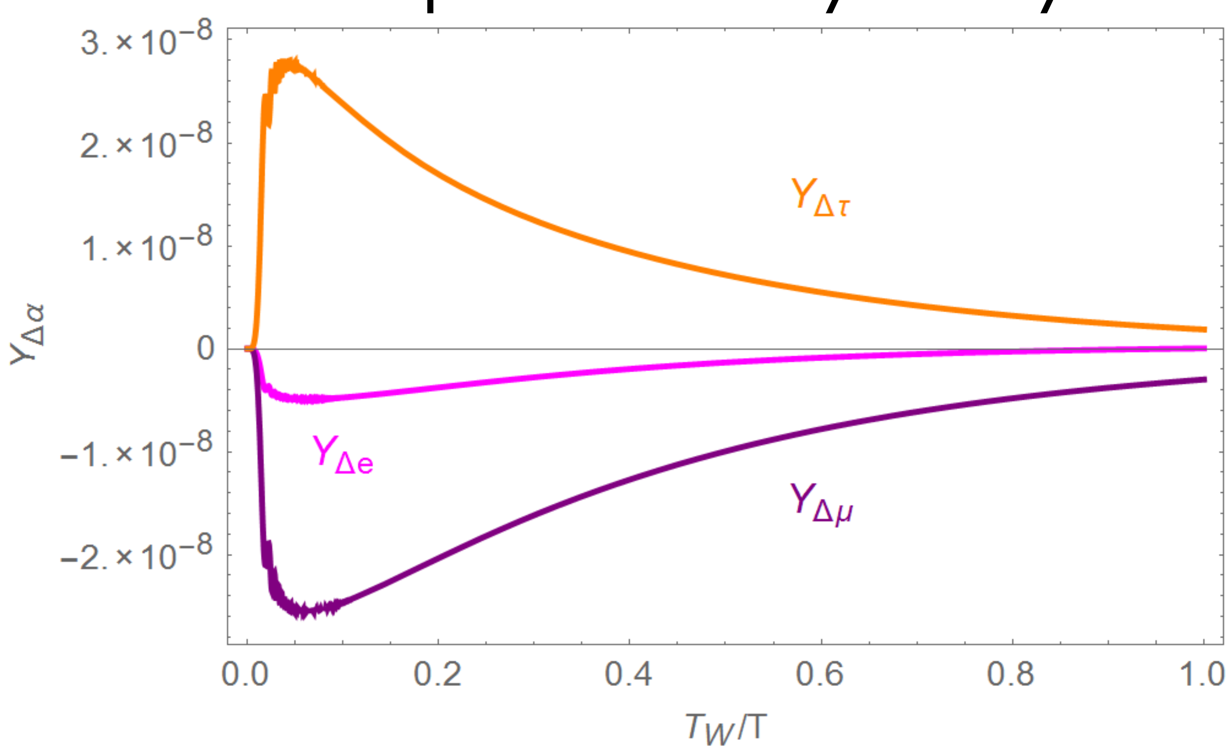
Sterile neutrino abundances

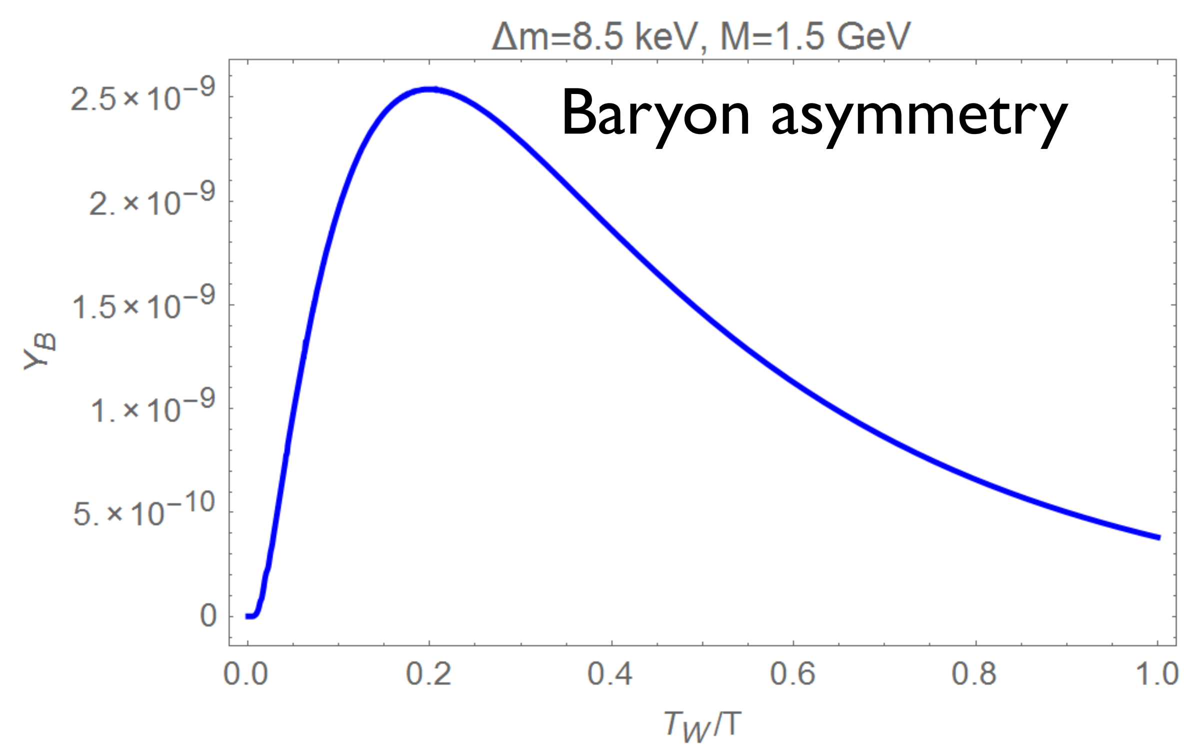


Sterile neutrino asymmetry



Lepton flavour asymmetry





Conclusions

Lepton number violation as a key to low scale leptogenesis

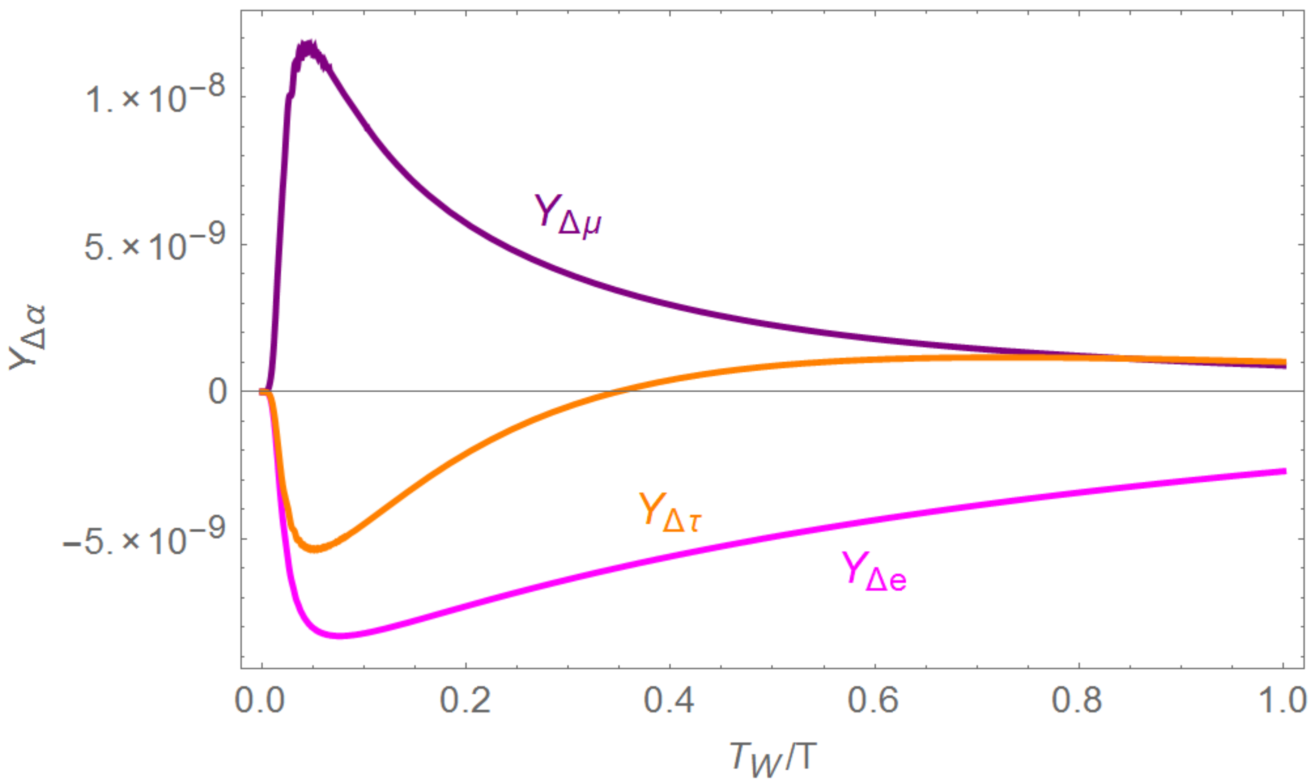
Analytical solution in the weak washout regime

Viable leptogenesis in weak washout , but solutions cannot be probed

Viable leptogenesis in strong washout , testable at future facilities

Backup

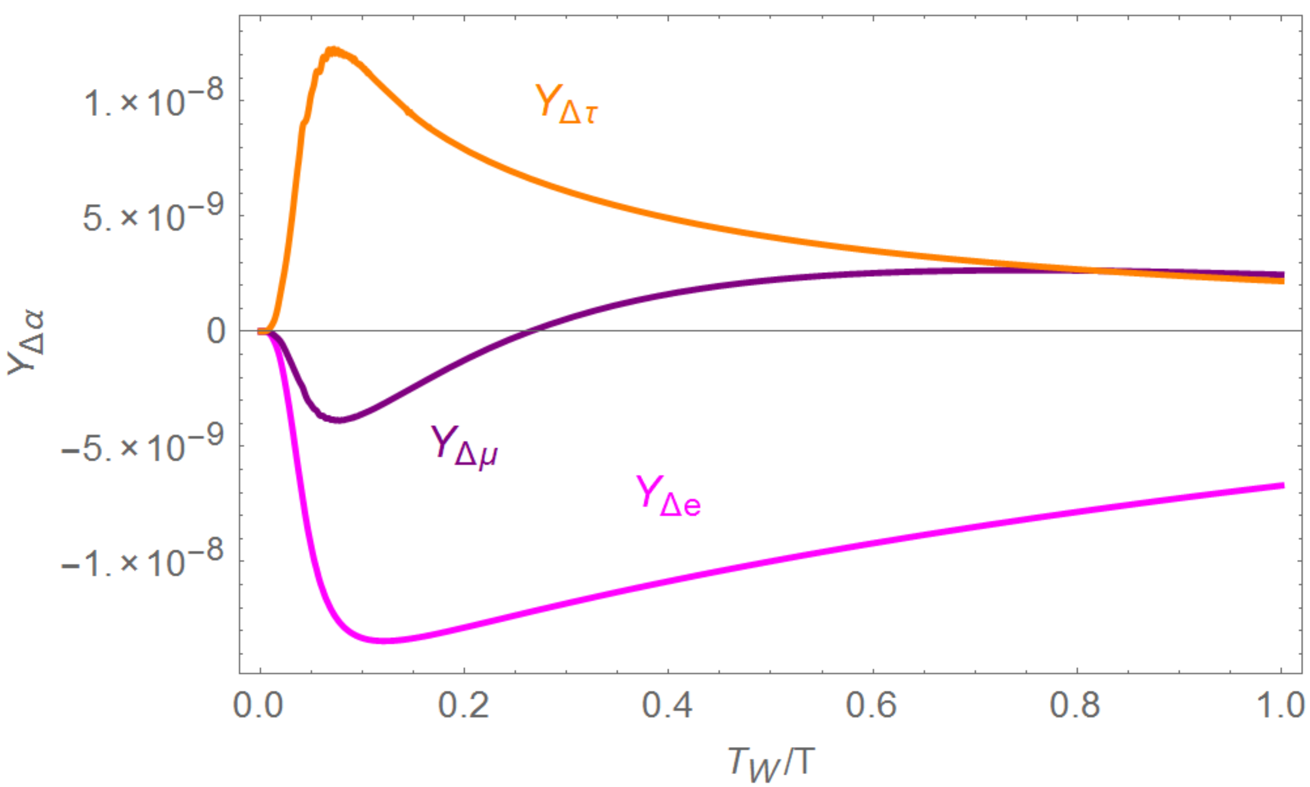
Strong washout regime: "flavoured" solutions



$M = 1\,\mathrm{GeV}, \quad \Delta m = 8.5\,\mathrm{keV}$

$$Y^{\mathrm{eff}} = \begin{pmatrix} -1.51\times10^{-7} - i\,1.30\times10^{-7} & -1.30\times10^{-7} + i\,1.51\times10^{-7} \\ -6.69\times10^{-8} - 7.07\times10^{-7} & -7.07\times10^{-7} + i\,6.68\times10^{-8} \\ 2.57\times10^{-8} - 3.92\times10^{-7} & -3.93\times10^{-7} - i\,2.57\times10^{-8} \end{pmatrix}$$

$$Y^{\mathrm{eff}}_{\mathrm{eq}} \simeq \sqrt{2}\times10^{-7}$$



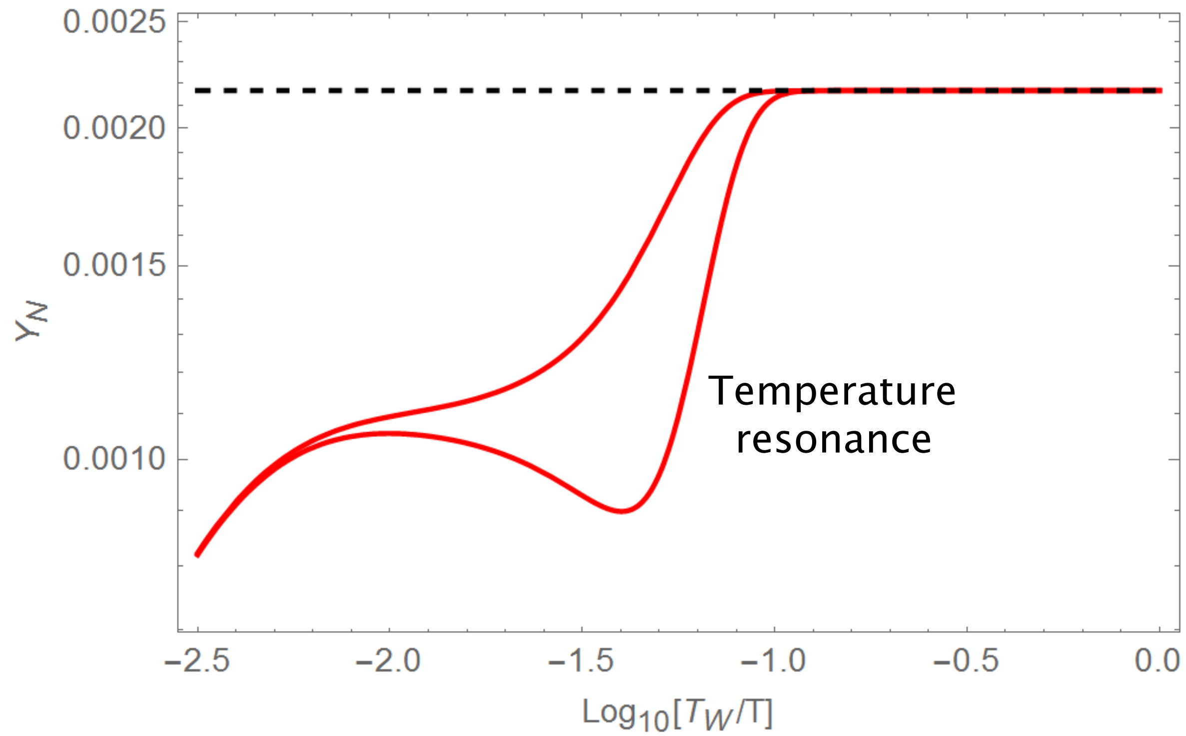
$M = 1.4\,\mathrm{GeV}, \quad \Delta m = 1.6\,\mathrm{keV}$

$$Y^{\mathrm{eff}} = \begin{pmatrix} 1.20\times10^{-7} + i\,1.08\times10^{-7} & 1.08\times10^{-8} - i\,1.20\times10^{-8} \\ 1.28\times10^{-8} - i\,3.60\times10^{-7} & -3.61\times10^{-7} - i\,1.28\times10^{-8} \\ -4.41\times10^{-8} - i\,8.29\times10^{-7} & -8.30\times10^{-6} + i\,4.40\times10^{-8} \end{pmatrix}$$

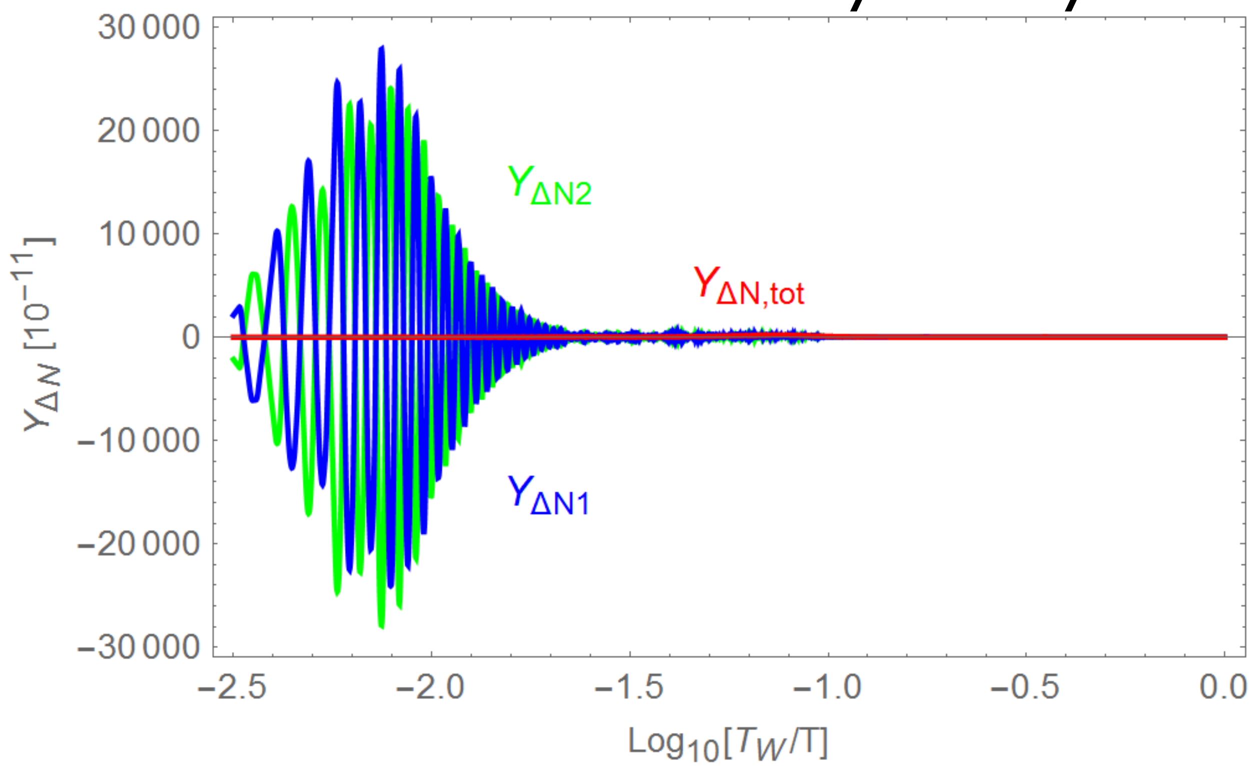
Strong strong washout regime

$$Y^{\rm eff} \approx \mathcal{O}\left(10^{-6}\right)$$

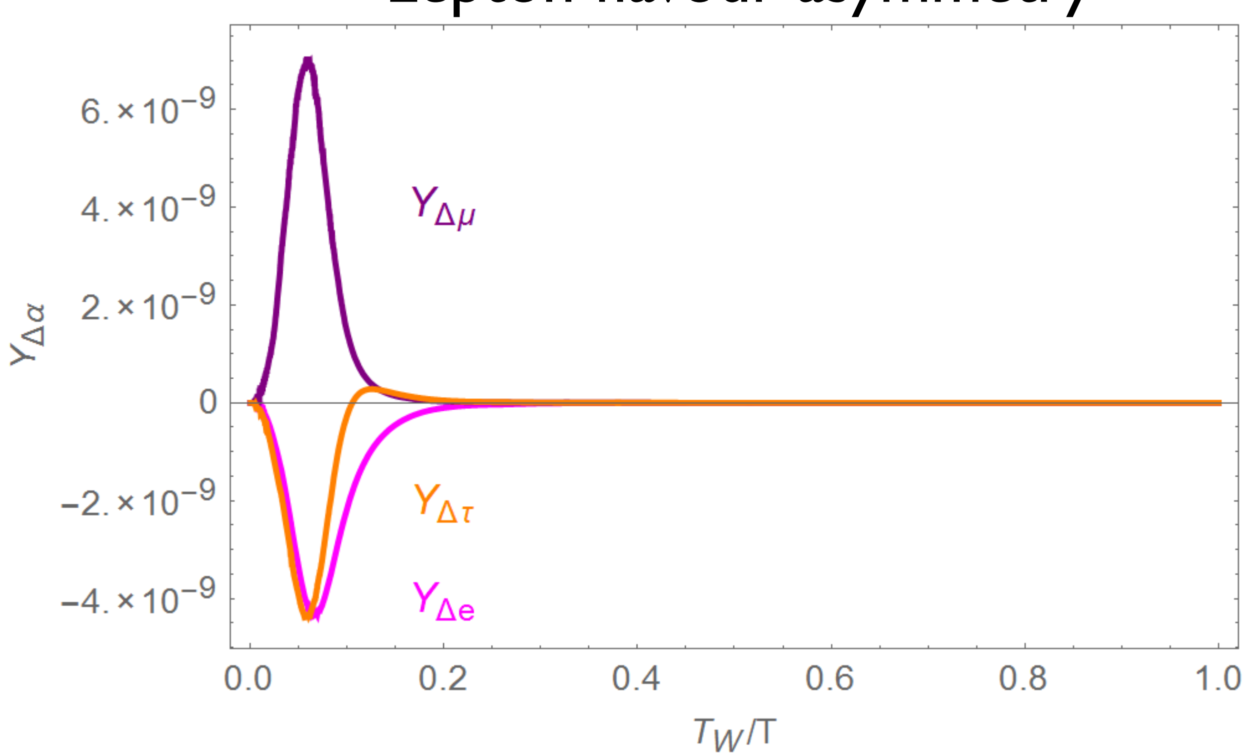
Sterile neutrino abundances

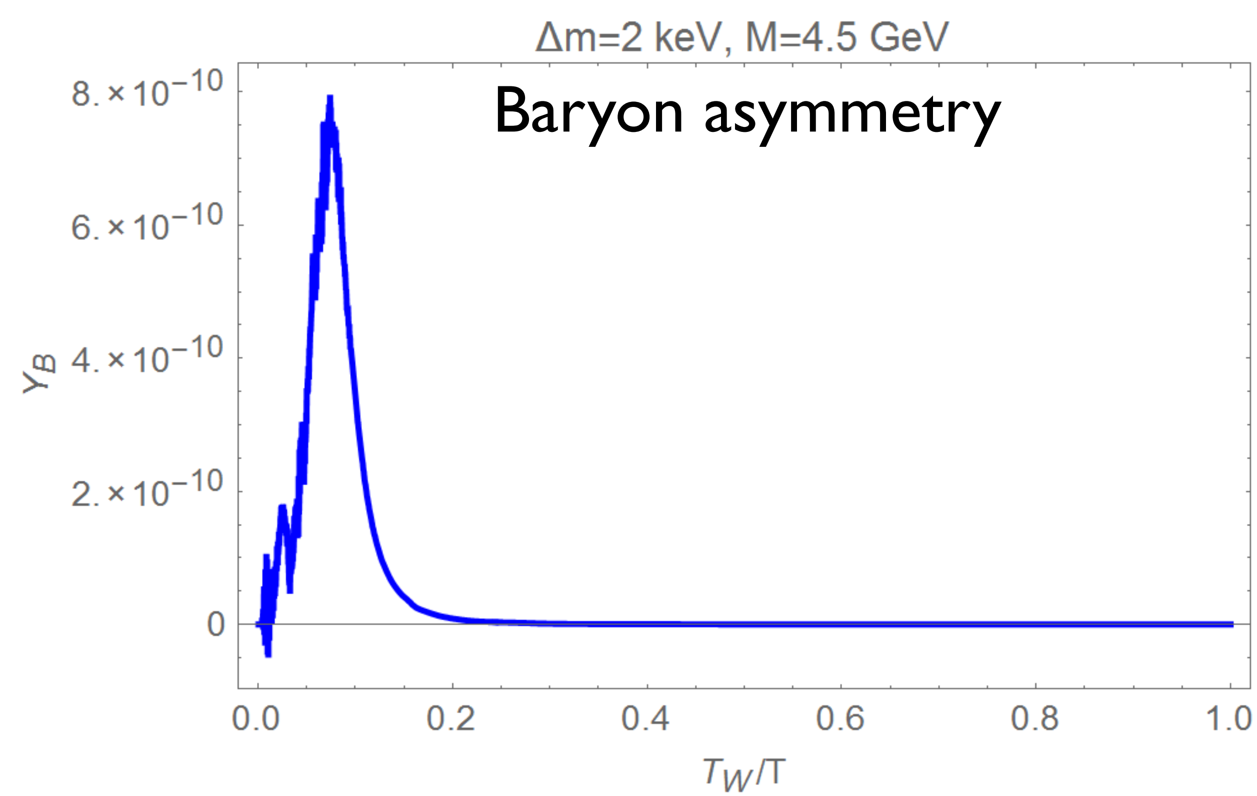


Sterile neutrino asymmetry

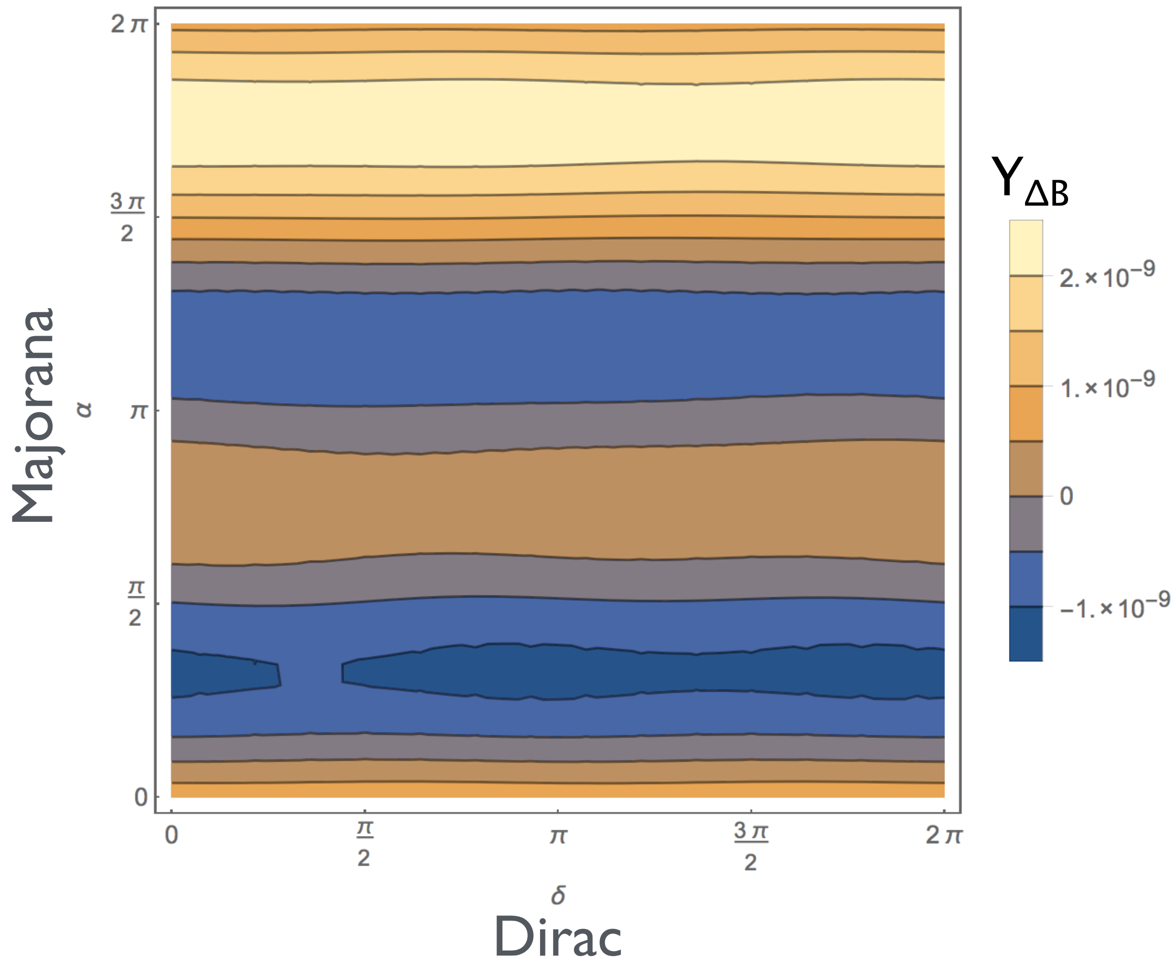


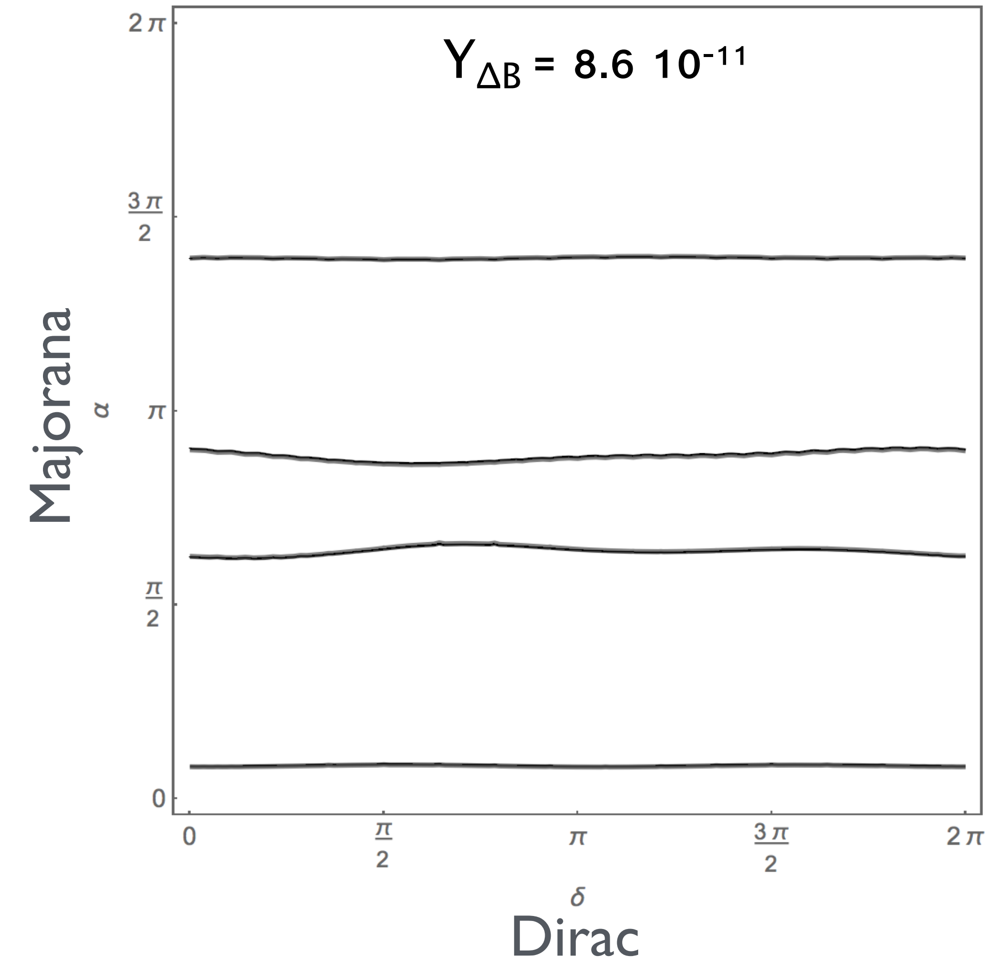
Lepton flavour asymmetry





Dirac and Majorana phase dependence





Strong dependence on **Majorana** phase

Weak dependence on **Dirac** phase

$$\mathcal{M} = \begin{pmatrix} 0 & vY & \epsilon v Y' \\ vY^{\mathrm{T}} & 0 & \Lambda \\ \epsilon v Y'^{\mathrm{T}} & \Lambda & \zeta \Lambda \end{pmatrix}$$

3 complex phases

U_{PMNS} with one massless ν

2 complex phases

Dirac
+
Majorana

The ISS setup

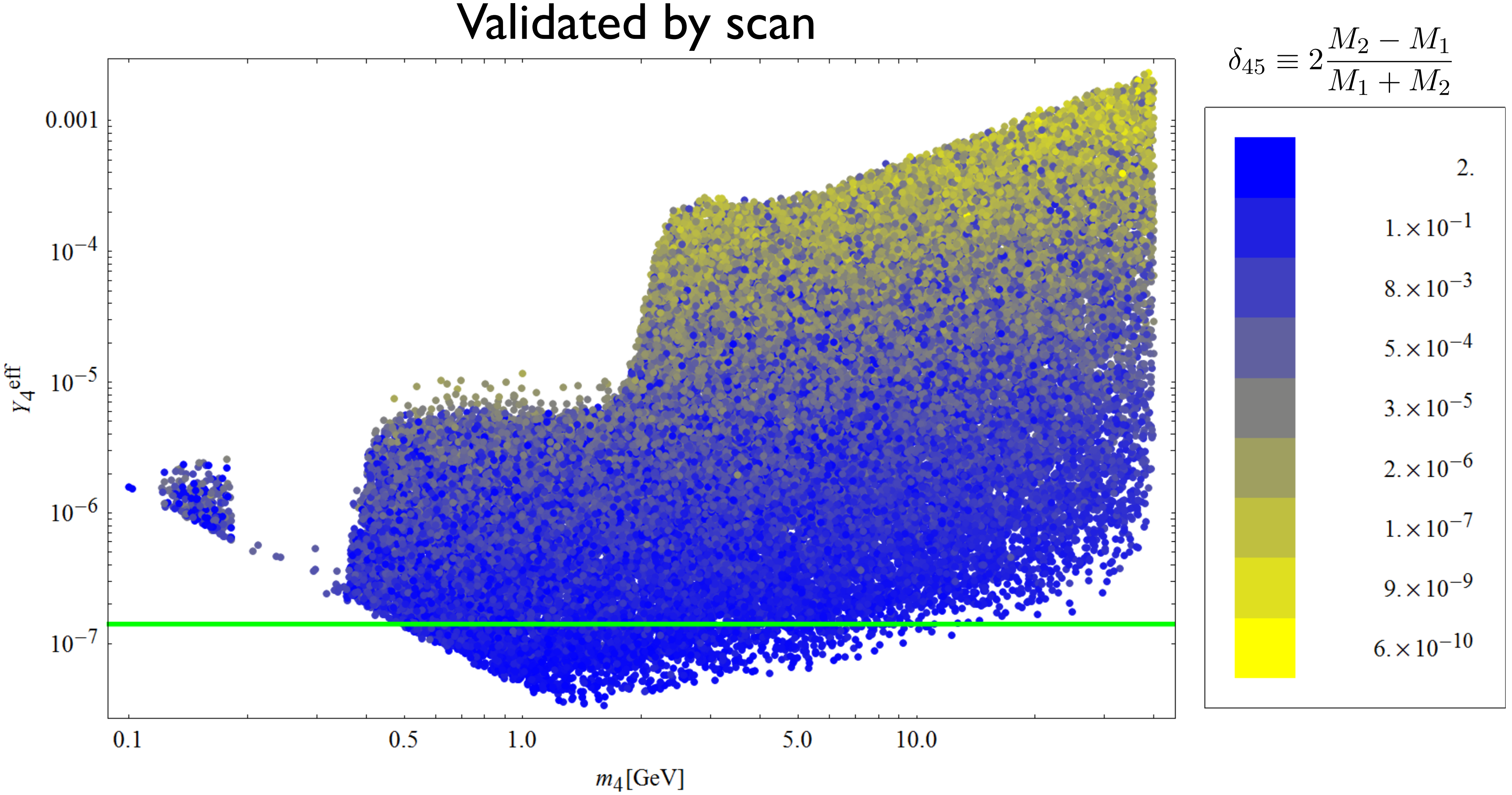
$$M = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} Y v & 0 \\ \frac{1}{\sqrt{2}} Y^T v & 0 & Z\Lambda \\ 0 & Z^T \Lambda & \xi \Lambda \end{pmatrix}$$

We show that neutrino data impose a lower bound on the Yukawa couplings

$$\sum_{i=4}^{9} \sum_{\alpha=1}^{3} |Y^{\rm eff}_{\alpha i}|^2 \geq 2 \frac{0.05 \text{ eV}}{\max|\xi_{jj}|} \frac{\Lambda}{v^2}$$

Imposing $Y^{\rm eff} < \sqrt{2} \times 10^{-7}$ → $\Delta M^2_{IJ} \simeq \xi \Lambda^2 \gtrsim (0.25 \text{ Gev})^2$ for $\Lambda > 1$ GeV

Validated by scan



No viable leptogenesis in the weak washout regime in the ISS setup